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Abstract

While carbon dioxide emissions from energy use must be the primary target of climate change mitigation efforts, land use and land cover change (LULCC) also represent an important source of climate forcing. In this study we compute time series of global surface temperature change separately for LULCC and non-LULCC sources (primarily fossil fuel burning), and show that because of the extra warming associated with the co-emission of methane and nitrous oxide with LULCC carbon dioxide emissions, and a co-emission of cooling aerosols with non-LULCC emissions of carbon dioxide, the linear relationship between cumulative carbon dioxide emissions and temperature has a two-fold higher slope for LULCC than for non-LULCC activities. Moreover, projections used in the Intergovernmental Panel on Climate Change (IPCC) for the rate of tropical land conversion in the future are relatively low compared to contemporary observations, suggesting that the future projections of land conversion used in the IPCC may underestimate potential impacts of LULCC. By including a ‘business as usual’ future LULCC scenario for tropical deforestation, we find that even if all non-LULCC emissions are switched off in 2015, it is likely that 1.5 °C of warming relative to the preindustrial era will occur by 2100. Thus, policies to reduce LULCC emissions must remain a high priority if we are to achieve the low to medium temperature change targets proposed as a part of the Paris Agreement. Future studies using integrated assessment models and other climate simulations should include more realistic deforestation rates and the integration of policy that would reduce LULCC emissions.

1. Introduction

The recent Paris COP21, with the follow-up agreements by governments, and Marrakesh COP22, suggest hopeful steps towards real climate action on the part of governments (Newsroom 2015, Peters *et al* 2015). However, the goal of keeping climate warming below 2 °C is difficult or even impossible without drastic cutting of anthropogenic carbon dioxide (CO₂) emissions, especially from the energy sector (Peters *et al* 2015). Since emissions from land use change are currently estimated to be about 10% of

total anthropogenic carbon dioxide emissions (Le Quéré *et al* 2016), most of the current policy focus is on cutting fossil fuel carbon emissions to reach the 2 °C targets (Peters *et al* 2015).

However, recent studies highlight the importance of land conversion of natural lands to agriculture or pasture and the ensuing greenhouse gas emissions and their impact on radiative forcing of climate (Ward and Mahowald 2015, Ward *et al* 2014). Currently, although only 20% of the accumulated anthropogenic rise in carbon dioxide originates from land use and land cover change (LULCC), 40% of the net positive radiative

forcing from human activities is attributable to LULCC sources (Ward *et al* 2014). This is because the LULCC co-emissions of methane and nitrous oxide enhance warming, while co-emissions of cooling aerosols by non-LULCC processes, like fossil fuel burning tend to offset non-LULCC radiative forcing (Ward *et al* 2014). In addition, there is some evidence that deforestation rates estimated in the Representative Concentration Pathways (RCPs) used for the IPCC estimates of future climate (van Vuuren *et al* 2011) may underestimate tropical deforestation in the future (e.g. Ward *et al* 2014, Ward and Mahowald 2015, Ciais *et al* 2013).

Much of the recent framing of the climate change challenge has focused on cumulative carbon dioxide emissions as a tool to estimate future warming, since studies have shown across a large range of scenarios that there is an approximately linear relationship between cumulative carbon dioxide emissions and temperature change up to 2100 (Matthews *et al* 2009, Allen *et al* 2009, Stocker *et al* 2013). This powerful linear relationship motivates much of how we think about climate and impacts climate policy, and specifically motivates the focus of climate policy on carbon dioxide emissions. The approach is especially useful for understanding the importance of moving from a high to low fossil fuel emission scenarios (Friedlingstein *et al* 2014). Using this framework, here, we use a previously published time-series of global radiative forcing computed separately for the LULCC and non-LULCC sectors of anthropogenic activities based on the RCPs (Ward *et al* 2014, Ward and Mahowald 2015) to determine each sectors' individual impact on the relationship between the cumulative carbon dioxide emission and temperature. In addition, we seek to understand the importance of the current rate of deforestation, if it continues, for climate, especially in the light of the ambitious climate targets from the Paris Agreement.

2. Methods

We use previously published radiative forcing (RF) time series that were calculated for LULCC and other non-LULCC sources separately, and for different future scenarios using a hierarchy of models including the Community Land Model (CLM) within the Community Earth System Model (Hurrell *et al* 2013, Lawrence *et al* 2012a). These simulations are described in detail elsewhere (Ward *et al* 2014, Ward and Mahowald 2015). Here we review only the basics of these calculations, and then indicate where new calculations were made for this study, with more details provided in the supplemental material available at stacks.iop.org/ERL/12/094016/mmedia.

Our approach was to start with the RCPs used in the Coupled Model Intercomparison Project (CMIP5) that were generated and analyzed as part of the last Intergovernmental Panel on Climate Change (IPCC)

(Clarke *et al* 2007, Fujino *et al* 2006, Riahl *et al* 2007, van Vuuren *et al* 2007, Wise *et al* 2009, Lamarque *et al* 2010, van Vuuren *et al* 2011, Ward *et al* 2014, Ward and Mahowald 2015). The difference between the estimates reported here (published in Ward *et al* 2014, Ward and Mahowald 2015) and previous estimates is that here we separated the radiative forcing into LULCC and non-LULCC components. Generally, our LULCC forcing included all related global-scale processes: land conversion, harvesting, agriculture emissions, agriculture fires, reduced wildfires from land conversion, and pasture use. We included all fossil fuel emissions in the non-LULCC emissions, along with concrete production and halocarbon emissions. Carbon dioxide emissions from LULCC were determined from global terrestrial model simulations using the CLM with historical and projected LULCC compared to a simulation without LULCC, using identical non-LULCC forcings (non-LULCC forcings follow RCP4.5 for 2005–2100). Associated changes in land surface albedo due to LULCC, as well as changes in emissions from wildfires and biogenic sources resulting from land cover changes, also were represented in these simulations. Agricultural emissions of trace gases and aerosols, including from agricultural fires, were compiled from existing inventories developed for the RCPs (Lamarque *et al* 2010, van Vuuren *et al* 2011, Ward *et al* 2014, Ward and Mahowald 2015).

The previous studies (Ward *et al* 2014, Ward and Mahowald 2015) that we drew upon in this paper used a combination of box model methods for long-lived forcing agents (greenhouse gases) and a global atmospheric model with aerosol/cloud interactions and complex chemistry to compute changes in concentrations of chemically-reactive, climatically important forcing agents due to LULCC. These calculations showed that the net impact of LULCC on methane was larger than the non-LULCC impact on methane, despite similar emissions from each sector, because non-LULCC emissions of nitrogen oxides and volatile organic compounds increased the oxidative capacity of the atmosphere which reduced the lifetime of methane, and thus reduced atmospheric methane as discussed in more detail in (Ward *et al* 2014). Anthropogenic nitrous oxide emissions were largely due to LULCC processes, and thus anthropogenic nitrous oxide radiative forcing also was predominately determined to be due to LULCC (Ward *et al* 2014). A previous study looked explicitly at the role of land conversion versus land management emissions, and split the results between these two processes (Ward and Mahowald 2015).

The estimates of radiative forcing used here that come from previous studies were made in a manner to ensure consistency with the IPCC 5th Assessment Report (Stocker *et al* 2013, Ward *et al* 2014, Ward and Mahowald 2015). Global radiative forcing values were computed at years 2010 and 2100, relative to a base

state of 1850, for changes in CO₂, CH₄, N₂O, O₃, halocarbons, aerosol (black carbon, organic carbon, sulfate, mineral dust) direct effects, aerosol indirect effects, aerosol impact on snow surface albedo, and land albedo change. Total anthropogenic aerosol radiative forcing calculated in our model was scaled to match best estimates from the last IPCC (Myhre *et al* 2013), since these forcings from aerosols were overestimated in our model similar to most models (Myhre *et al* 2013).

For this study, we computed the time-varying radiative forcing to show the evolution of the LULCC vs. non-LULCC contributions to radiative forcing and temperature. Interpolation between 1850 and 2010, and between 2010 and 2100, was done for the individual forcing agents by scaling the RF linearly with changes in the emissions of the agent or relevant precursor species, such as NO_x for the O₃ forcing (Ward and Mahowald 2015). Uncertainties in the radiative forcing values, computed for the year 2010 by Ward *et al* (2014), were scaled by the same methodology.

Ward *et al* (2014) report future LULCC and non-LULCC radiative forcing estimates for each of the four RCP scenarios. In addition, we evaluated a non-RCP-based scenario, which assumes that tropical deforestation continues into the future at current rates (FAO 2010). This scenario was first presented in Ward and Mahowald (2015). We focused on the tropics, because much of the deforestation currently occurs in the tropical regions (FAO 2010). As described in more detail in Ward and Mahowald (2015), the tropical business-as-usual (TBAU) land cover change scenario extended the country-by-country forest area decreases estimated by the FAO (2010) for 2000–2010 to the time interval between 2010 and 2100 for the tropics only. Future tropical deforestation was limited to 1°x1° grid locations where past deforestation had occurred, except in the case of completely deforested areas for which deforestation spread was distributed in adjacent forests. Outside of the tropics the land cover changes from the TBAU followed those of RCP8.5. Small rates of reforestation were reported in tropical Southeast Asia between 2000 and 2010 but we only consider tropical forest loss in the TBAU scenario. Global wood harvesting and forest area changes, including reforestation, outside of the tropics follow the RCP8.5 projection (Lawrence *et al* 2012b). Deforested land was replaced with 80% cropland and 20% pasture following contemporary tropical estimates (Houghton 2012). Agricultural emissions of CH₄ and N₂O for the year 2100 were scaled in the TBAU scenario by the increase in crop and pasture lands relative to the RCP8.5 scenario in 2100, assuming the same emission rates per unit cultivated area in both scenarios for tropical latitudes. The TBAU scenario developed in Ward and Mahowald (2015) and used here was not developed in connection with integrated assessment modeling and, therefore, the land cover changes did not respond to economic or demographic drivers or

feedbacks. It instead projects a world in which current land use practices are simply continued, which is roughly consistent with the IAM-based RCP projections. The realism of this scenario should in future studies be explored in IAM models that can include these processes (e.g. Riahi *et al* 2017), but simultaneously are able to simulate current observed deforestation rates.

To estimate future climate change in this study, we introduced two additional scenarios in which LULCC and non-LULCC emissions were switched off, in turn, at the year 2015. While there are no further emissions of any trace gas or aerosol from these sources after 2015 in these scenarios, atmospheric concentrations from pre-2015 emissions still influenced the radiative forcing, and therefore the evolution of the climate. Aerosol and ozone forcings diminished to zero within a year given their short atmospheric residence times, but long-lived greenhouse gases decay according to typical atmospheric lifetimes following Ward and Mahowald (2014). The CO₂ concentration response to the emissions switch-off was determined using a pulse response function (Enting *et al* 1994) as described in Ward *et al* (2014) and Ward and Mahowald (2014).

For the scenario in which non-LULCC emissions were switched off in 2015, the global CO₂ concentration was substantially lower in year 2100 than for the scenarios with all emissions used to compute RFs in Ward *et al* (2014). Since the radiative forcing of a perturbation to CO₂ concentration is sensitive to the background CO₂ level, we recalculated the LULCC CO₂ radiative forcing time series for this scenario with the new, lower global CO₂ concentration. The RF from N₂O and CH₄ is less sensitive to the change in background concentrations that results from the emissions switch-off and these terms were not recomputed. Short-lived forcing agents, including aerosols, were also not recalculated since the contribution of LULCC to these forcing terms is small.

We computed time series of global average surface temperature change using the energy-balance component of the MAGICC6 reduced complexity climate model (Meinshausen *et al* 2011), following a similar methodology as used in Ward and Mahowald (2014), and described briefly here. The MAGICC6 energy balance was forced with the radiative forcing time series constructed for the different scenarios as described above. Since the equilibrium climate sensitivity was prescribed in MAGICC6, the choice of a value for this parameter governs the resulting temperature change for a given radiative forcing time series. Therefore, for each RF scenario we ran a 5000-member ensemble of global average surface temperature change for 1850 to 2100. Each ensemble member used a unique equilibrium climate sensitivity that was randomly selected from a gamma distribution that was constructed to match the qualitative probabilities laid out in the IPCC AR5 as quantified by Rogelj *et al* (2014).

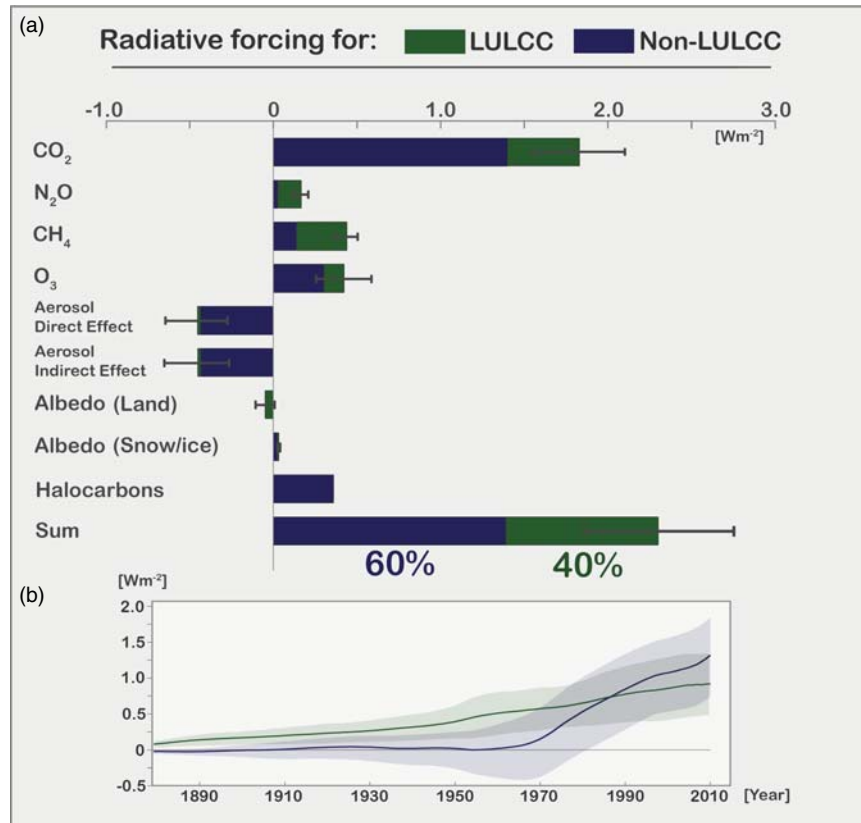


Figure 1. (a) Anthropogenic radiative forcing (Wm^{-2}) for the year 2010 relative to 1850 partitioned into LULCC and non-LULCC sources for different forcing agents, with uncertainty in the portion of total radiative forcing due to LULCC given by the error bars (adapted from Ward *et al* 2014). (b) Timeseries of anthropogenic radiative forcing (Wm^{-2}) for LULCC and non-LULCC sources with uncertainty represented by the shading.

The IPCC AR5 does not define a ‘best guess’, median equilibrium climate sensitivity so here we defined the gamma distribution median as 2.4 K, the value of the equilibrium climate sensitivity that lead to the best match between MAGICC6 and the observed global mean surface temperature anomaly (relative to preindustrial) for the period 1980–2010, determined by the least-squares method. We fit a gamma distribution with a shape parameter equal to 5 to the (Rogelj *et al* 2014) probability ranges, which, because of the low median equilibrium climate sensitivity relative to the possible range in equilibrium climate sensitivity values (0.5 K to 8.0 K), skews somewhat toward lower values of equilibrium climate sensitivity than estimated by the IPCC AR5.

3. Results

3.1. Cumulative carbon dioxide emissions relationship with temperature

In 2015, although only 10% of the current emissions of CO_2 derive from LULCC (Le Quéré *et al* 2016), 20% of the accumulated anthropogenic rise in CO_2 concentrations originates from LULCC (figure 1(a), Ward *et al* 2014). The enhanced impact of LULCC on anthropogenic CO_2 occurs because LULCC was a proportionally larger source of CO_2 emissions

during the 20th century (Le Quéré *et al* 2016), there is still substantial contribution of previously emitted LULCC to atmospheric concentrations (figure 1(a)). Currently, although only 20% of the accumulated anthropogenic rise in carbon dioxide originates from land use and land cover change (LULCC), 40% of the net positive radiative forcing from human activities is attributable to LULCC sources (Ward *et al* 2014). The effective LULCC radiative forcing is enhanced by LULCC emissions of methane and nitrous oxide (figure 1(a)). The other anthropogenic greenhouse gas sources (non-LULCC) derive partially from fossil fuel CO_2 , but include CO_2 from cement production and halocarbons. The impact of the radiative forcing of the non-LULCC emissions is partially offset through co-emissions of aerosols; these aerosols cause a net negative, or cooling, radiative forcing (Ward *et al* 2014) (figure 1(a)). While at present similar amounts of methane are emitted by LULCC and non-LULCC sources, co-emissions from non-LULCC sources enhance the oxidative capacity of the atmosphere and reduce the methane lifetime relative to the LULCC case, leading to a smaller methane RF attributed to non-LULCC emissions (Ward *et al* 2014).

LULCC was the dominant driver of positive anthropogenic radiative forcing until the 1980s (figure 1(b)), in part because of the considerable contribution of CO_2 emissions from this sector relative to other

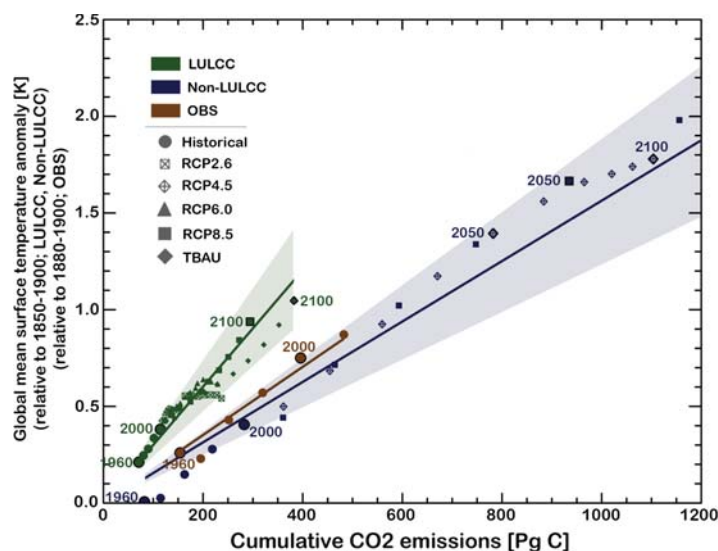


Figure 2. Change in global mean surface temperature relative to the 1850–1900 mean for cumulative carbon dioxide emissions from different LULCC and non-LULCC scenarios. The temperature increase associated with the cumulative carbon dioxide emissions (but including other emissions and forcings) is plotted for every ten years in the 1850–2100 time series with historical points (circles), RCP2.6 (x), RCP4.5 (crosses), RCP6.0 (triangles), RCP8.5 (squares) and tropical business as usual (TBAU) (diamonds) for land use and land cover change (LULCC), shown in green. The temperature increase for other sources of anthropogenic forcing (labeled non-LULCC) in blue using RCP4.5 (crosses), and RCP8.5 (squares). The radiative forcings are calculated in (Ward and Mahowald 2015, Ward *et al* 2014) for LULCC versus other sources (non-LULCC). The observed temperature is shown in brown using GISS temperature observations and estimated cumulative emissions. The interquartile range is determined from the MAGICC6 simulation ensemble and the regression lines are fit to yearly values for all historical and future scenario points between 1960 and 2100.

sources during first half of the 20th century (Le Quéré *et al* 2016). For the contemporary period, the overall net radiative forcing from LULCC (40%) is twice the proportion of the radiative forcing from CO₂ that can be attributed to be from LULCC (20%), indicating a two-fold enhancement of total radiative forcing (RF) relative to the CO₂ anomaly for LULCC compared with non-LULCC sources (figure 1) (Ward *et al* 2014).

LULCC impacts on climate change are also likely to be significant into the future (Ward and Mahowald 2015, Ward *et al* 2014, figure S1). The two-fold enhancement of total RF compared with RF from CO₂ for LULCC compared to non-LULCC is predicted for all the different RCPs used in the last IPCC at 2100 (van Vuuren *et al* 2011, Ward and Mahowald 2015, Ward *et al* 2014). Although these results are sensitive to assumptions regarding co-emissions of aerosols and non-CO₂ greenhouse gases, the forcing differences are surprisingly robust across the various RCPs and historical estimates (Ward and Mahowald 2015, Ward *et al* 2014). Because aerosol emissions in the RCPs are projected to decrease at a possibly unrealistic rate (Schindell *et al* 2013), the non-LULCC contribution to overall temperature change may even be smaller than these estimates.

This suggests that while the linear relationship between cumulative carbon dioxide emissions and temperature may work well for the net impact anthropogenic activity over a variety of scenarios (Allen *et al* 2009, Stocker *et al* 2013), a different, steeper slope should be used when considering the influence of LULCC compared to non-LULCC (figure 2,

0.0030 K PgC⁻¹ vs. 0.0016 K PgC⁻¹). Until the 1970s, non-LULCC CO₂ emissions were associated with a zero net radiative forcing (figure 1), which results in a zero net impact on temperature, and then later the slope with respect to cumulative carbon emissions steepens, as the co-emitted species change (figure 2). The observed line (based on 1960–2010 observed temperatures) has a similar slope and intercept as to the non-LULCC CO₂ emission line (based on 1960–2100 predicted temperatures), as during this time period especially, there is a stronger contribution from non-LULCC to current warming (e.g. figure 1).

Effectively, the slopes (m_{LULCC} and $m_{\text{non-LULCC}}$) in figure 2 represent the following processes:

$$m_{\text{LULCC}} = \left(\frac{\Delta T}{\Delta \text{RF}} \right) \frac{(\text{RF}_{\text{CO}_2} + \text{RF}_{\text{CH}_4} + \text{RF}_{\text{N}_2\text{O}} + \text{RF}_{\text{aerosols}})}{\sum \text{Emis}_{\text{LULCC}}(\text{CO}_2)}$$

$$m_{\text{non-LULCC}} = \left(\frac{\Delta T}{\Delta \text{RF}} \right) \frac{(\text{RF}_{\text{CO}_2} + \text{RF}_{\text{CH}_4} + \text{RF}_{\text{N}_2\text{O}} + [\text{RF}_{\text{aerosols}}])}{\sum \text{Emis}_{\text{non-LULCC}}(\text{CO}_2)} \quad (1)$$

Where $(\Delta T/\Delta \text{RF})$ is the change in temperature per change in RF (called the climate sensitivity, and the colored areas around the points represent the spread due to uncertainties in the climate sensitivity, as described in section 2), and $\sum \text{Emis}(\text{CO}_2)$ is the cumulative carbon emissions, from either LULCC or non-LULCC processes up until different times (Stocker *et al* 2013). Strong positive and negative contributions are indicated in bold and put inside square brackets[], respectively. Weak contributions are shown in black or not included (relative contributions for each

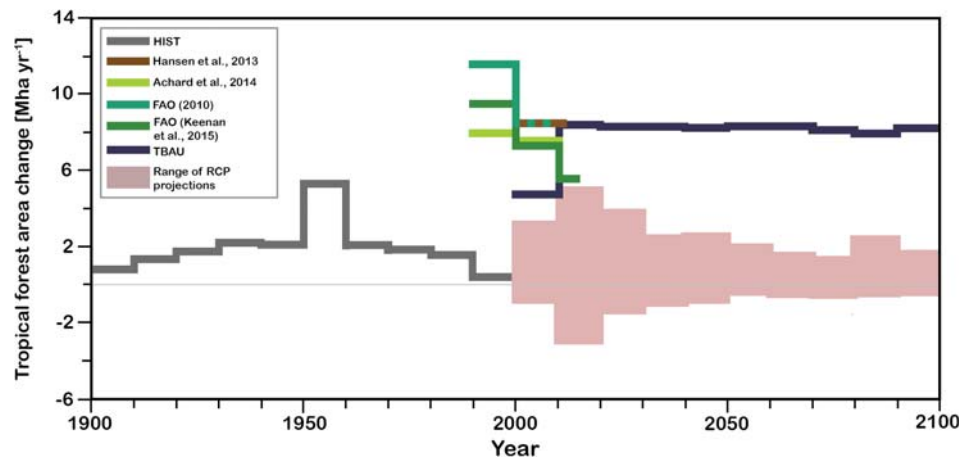


Figure 3. Decadal average change in tropical forest area for historical, contemporary, and future conditions. Historical forcing estimates used for CMIP5/IPCC (HIST: grey line; Hurtt *et al* 2006, Lawrence *et al* 2012b) are shown through 2000 with an averaging designed to reduce arbitrary changes in land cover due to changes in the datasets ('hand-shaking') done to be consistent with the range of CMIP5/IPCC RCPs (pink shading) across the 2000–2010 time period. The 4 different RCP future estimates all lie under the FAO estimates for the last 20 years (FAO 2010), satellite based estimates (Hansen *et al* 2013), and combined satellite and forest plot datasets (Achard *et al* 2014) (colored lines). Also shown is the tropical business as usual (TBAU) estimates of forest loss from (Ward and Mahowald 2015), based on FAO (2010) estimates for 2000–2010. Small changes in the deforestation rate occur in the TBAU case because of the methods used to project deforestation into the future.

forcing agent are shown in figure 1(a)). Uncertainties in these slopes originate from uncertainties in our understanding of the climate sensitivity, the magnitude of forcing associated with individual processes, and the response of global mean temperature to a particular radiative forcing (Stocker *et al* 2013). Since most of the positive RF from methane and nitrous oxide come from LULCC, and most of the negative RF from aerosols comes from non-LULCC (figure 1(a)), the non-LULCC cumulative carbon relationship with temperature at different times has a lower slope. The LULCC and non-LULCC slopes are much more similar, of course, if instead of considering cumulative carbon dioxide emissions, we consider equivalent carbon dioxide emissions (figure S2). Note also, that if deforestation rates were stabilized, but agriculture or pasture usage caused continued increases in methane or nitrous oxide emissions, the carbon dioxide emissions would be zero, but there would be a non-zero climate response, forcing the slope to be even higher (infinite).

3.2. Future climate sensitivity to deforestation rates

The Climate Model Intercomparison Project (CMIP) simulations used in the IPCC are based on the RCPs projections of future land use change or deforestation rates. Most contemporary deforestation is focused in tropics, and so we focus our discussion here on that region (FAO 2010). The combined historical and RCP scenario estimates used in Earth system models estimates of current deforestation rates in the tropics are less than those observed during the past two decades (figure 3) based on Food and Agriculture Organization (FAO) estimates (FAO 2010, Hurtt *et al* 2011, Meyfroidt and Lambin 2011, Ward *et al* 2014), although carbon emissions in the simulations

presented here during 2000–2010 are similar to other model and observationally-based estimates within the large uncertainties (Le Quéré *et al* 2016, Ward *et al* 2014). The future scenarios generated by the IAMs for the RCPs used to drive the CMIP5 earth system models in the most recent IPCC all simulate the same or lower rates of tropical deforestation than estimated today by FAO (figure 3). If we assume for simplicity that the IAMs are correct in projecting that the pressure for land conversion will remain the same as what is observed today, and we use observations to set the baseline rate during 2000–2010, we can estimate the influence of TBAU LULCC impacts on climate (Ward and Mahowald 2015).

Assuming all other anthropogenic emissions cease in 2015, the TBAU LULCC impacts will likely cause temperatures to increase more than 1.5 °C and potentially even more than 2 °C, relative to the pre-industrial era, by 2100 (figure 4(a)). This future-LULCC forced rise in temperature adds about 1 °C to the rise in temperature already in the pipeline from emissions that occurred prior to 2015 to produce the 1.5 °C warming (Hansen *et al* 2005) (figures 4(b) and (c)). At 2100 TBAU LULCC impacts can be as large as RCP4.5 non-LULCC climate impacts (figure 4(c); case ii vs. iii). The difference at 2100 between RCP4.5 and RCP8.5 non-LULCC is more than 1K (figure 5; v vs. vi) and is likely to grow larger after 2100. Our results are consistent with previous studies that emphasize climate change policy should focus on reducing CO₂ emissions from non-LULCC sources. However, about 1 °C rise in temperatures is associated solely with LULCC-TBAU, even with a moderate emission scenario for fossil fuels and other anthropogenic emissions, such as RCP4.5 (figure 4(c); case iii vs. v).

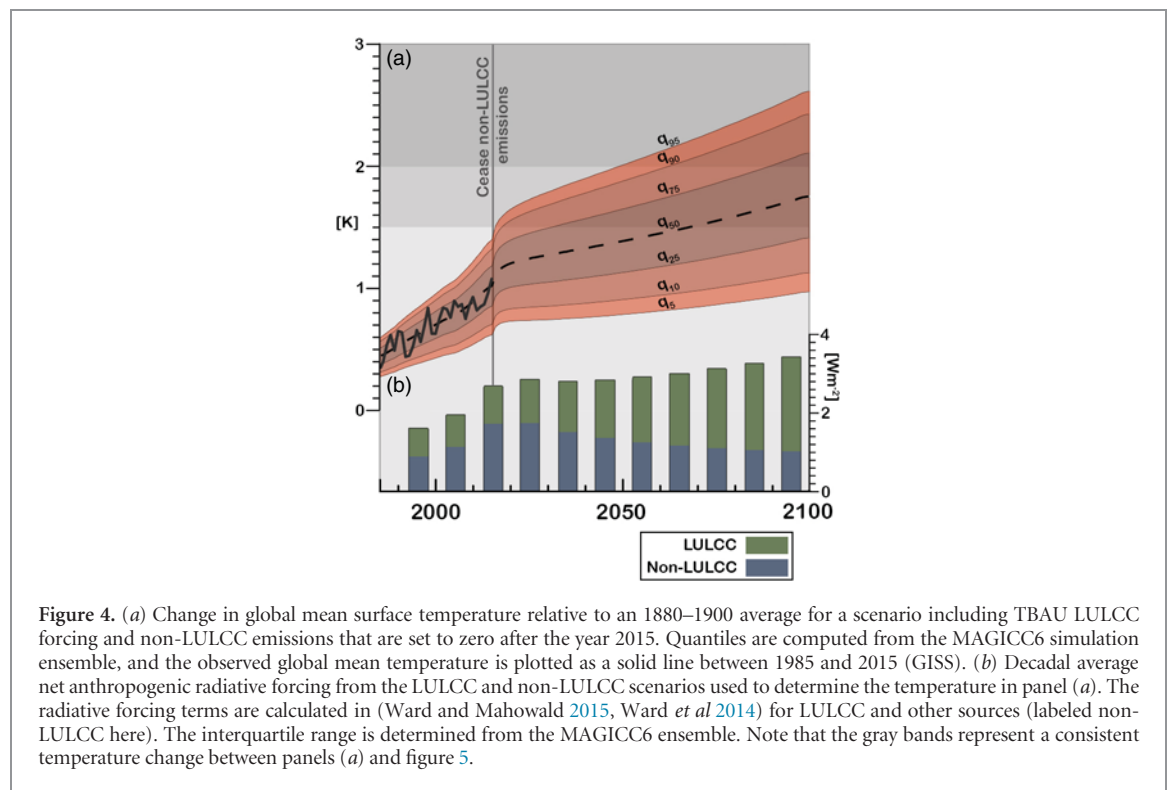


Figure 4. (a) Change in global mean surface temperature relative to a 1880–1900 average for a scenario including TBAU LULCC forcing and non-LULCC emissions that are set to zero after the year 2015. Quantiles are computed from the MAGICC6 simulation ensemble, and the observed global mean temperature is plotted as a solid line between 1885 and 2015 (GISS). (b) Decadal average net anthropogenic radiative forcing from the LULCC and non-LULCC scenarios used to determine the temperature in panel (a). The radiative forcing terms are calculated in (Ward and Mahowald 2015, Ward *et al* 2014) for LULCC and other sources (labeled non-LULCC here). The interquartile range is determined from the MAGICC6 ensemble. Note that the gray bands represent a consistent temperature change between panels (a) and figure 5.

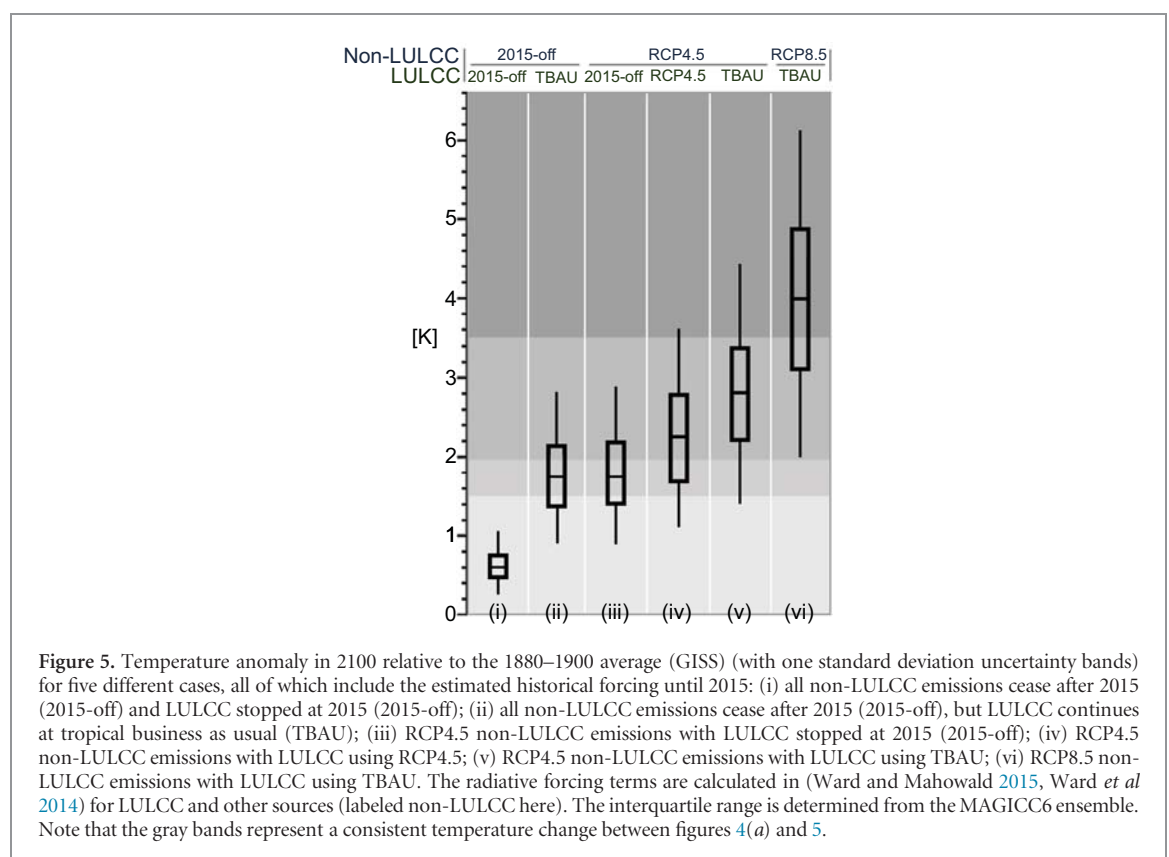


Figure 5. Temperature anomaly in 2100 relative to the 1880–1900 average (GISS) (with one standard deviation uncertainty bands) for five different cases, all of which include the estimated historical forcing until 2015: (i) all non-LULCC emissions cease after 2015 (2015-off) and LULCC stopped at 2015 (2015-off); (ii) all non-LULCC emissions cease after 2015 (2015-off), but LULCC continues at tropical business as usual (TBAU); (iii) RCP4.5 non-LULCC emissions with LULCC stopped at 2015 (2015-off); (iv) RCP4.5 non-LULCC emissions with LULCC using RCP4.5; (v) RCP4.5 non-LULCC emissions with LULCC using TBAU; (vi) RCP8.5 non-LULCC emissions with LULCC using TBAU. The radiative forcing terms are calculated in (Ward and Mahowald 2015, Ward *et al* 2014) for LULCC and other sources (labeled non-LULCC here). The interquartile range is determined from the MAGICC6 ensemble. Note that the gray bands represent a consistent temperature change between figures 4(a) and 5.

4. Discussion and conclusions

Here we show that the slope of the cumulative carbon dioxide emissions and temperature relationship is twice as high for LULCC than for non-LULCC processes (figure 2). This implies that carbon dioxide emissions

from LULCC is associated with twice the impact on climate as carbon dioxide emissions from non-LULCC processes, at least until 2100. This is due to the larger contributions of the warming greenhouse gases methane and nitrous oxide from LULCC to global RF relative to LULCC carbon dioxide emissions, and

the larger cooling from co-emitted aerosols from non-LULCC per unit emission of carbon dioxide (figure 1(a); Ward *et al* 2014). The impact of these emissions in future scenarios on climate will be very sensitive to the assumptions about the emissions of aerosols (from non-LULCC) and methane and nitrous oxide from LULCC sources (figure 1(a)), but these results are surprisingly robust across the multiple IAMs used for the RCPs (Ward *et al* 2014). They may also underestimate the effect of aerosols into the future, as all of the RCPs assume very strong cuts in aerosol emissions in the short term (Van Vuuren *et al* 2011, Shindell *et al* 2013). While the use of the linear relationship between temperature response and cumulative carbon dioxide emissions is helpful in contrasting very high CO₂ and low CO₂ future scenarios, for medium to low CO₂ scenarios, using metrics which include other green house gases and aerosols is important (e.g. Allen *et al* 2016).

Additionally, the LULCC contribution to future warming may be of greater importance than is currently thought because it is likely that the land use scenarios used in the IPCC are underestimating the current land use conversion rate. FAO estimates are higher than those used to derive future warming in the IPCC (FAO 2010, Hurtt *et al* 2011, Meyfroidt and Lambin 2011, Ward *et al* 2014) (figure 3) and recent observationally-based estimates of deforestation suggest that deforestation now may be larger than estimated from FAO (Achard *et al* 2014, Hansen *et al* 2013) (figure 3). It is difficult to derive deforestation rates, however, from Landsat satellite observations because some changes in forest area are not caused by deforestation or other forms of land management, but by natural processes. Indeed there can also be shifting cultivation or wood harvesting areas, allowing regrowth. This suggests that we can only use the observational estimates as upper bounds on deforestation rates (Achard *et al* 2014, Hansen *et al* 2013), but these observational estimates and FAO estimates are larger than the forcing datasets used in the IPCC. Thus, our TBAU estimates may be considered a reasonable upper bound on future rates of change, but require further refinement.

Loss of tropical forest cover also weakens the response of the terrestrial biosphere to accumulate carbon in response to rising levels of atmospheric CO₂ (Gitz and Ciais 2003, Mahowald *et al* 2017). This considerably weakens the carbon-concentration feedback, accelerating climate warming (Mahowald *et al* 2017).

Estimates suggest the rates in Amazonian deforestation in Brazil have been increasing again, showing the vulnerability of tropical forests to global agricultural expansion (Tolleson 2016). The future scenarios generated by the IAMs and used in the CMIP5 earth system models used in the most recent IPCC simulate the same or lower rates of tropical deforestation than estimated today by the FAO (figure 3). Of course, future land conversion is difficult to project. While future crop yield projections are sensitive to assumptions

about the ability of humans to innovate both management methods and genetic attributes (Fischer *et al* 2005), some evidence suggests that yield improvements may already be decreasing (Ray *et al* 2012) and that agricultural crops may be more sensitive to temperature than previously estimated (Lobell *et al* 2011). Thus we may require more land in the future for the same food production. Recent studies highlight the potential dangers of foreign land acquisition in many poorer countries, as rapidly developing countries try to purchase available land and 'outsource' their LULCC (Rulli *et al* 2013), which may also drive additional deforestation. In addition, most of the emission projections that stay at or below the 2 °C warming target require substantial negative emissions, often using land-based biofuels and carbon sequestration (Smith *et al* 2016). Thus, there is a potentially large, systematic low bias in future projections of LULCC deforestation and land conversion rates, and the resulting impact on climate (Ward *et al* 2014). Taken together, these recent developments suggest that reductions in land use conversion, especially of forests in tropical countries, as assumed in the RCPs, may not occur without considerable international effort. Using a more realistic estimate of tropical-business-as-usual conversion of forests, we estimate about 1 °C rise in temperature will result by 2100 solely due to LULCC, with a substantial probability of exceeding 2 °C warming relative to preindustrial temperatures even without non-LULCC emissions (figure 4). Since both the deforestation itself, as well as the land management emissions from agriculture or pasture usage contribute roughly equally to the LULCC radiative forcing (Ward and Mahowald 2015), policy measures directed at LULCC should address both deforestation rates, as well as agricultural emissions (Foley *et al* 2011, Kauppi *et al* 2006, Lambin and Meyfroidt 2011, Chabbi *et al* 2017). Policy tools can provide incentives for farmers to reduce emissions from fertilizer use, rice cultivation and livestock, for example (Foley *et al* 2011, Kauppi *et al* 2006, Lambin and Meyfroidt 2011, Chabbi *et al* 2017).

Fundamentally, LULCC is driven by the need for food and shelter. We can use land more efficiently with less environmental impacts (Foley *et al* 2011, Kauppi *et al* 2006, Lambin and Meyfroidt 2011, Chabbi *et al* 2017), but land-based agriculture requires arable land. Although humans have recently been successful at obtaining more food from the oceans (FAO 2016), this may be difficult in the future as these ecosystems are also heavily exploited (Watson *et al* 2013). In contrast, at least theoretically, there are methods for producing sustainable energy without producing carbon dioxide (IPCC 2014). Thus in some ways LULCC emissions may be just as difficult or more difficult to mitigate than energy (Lambin and Meyfroidt 2011). More realistic consideration of LULCC is needed in IAM projections used for IPCC assessments (e.g. Riahi *et al* 2017), so that the many policy choices and tools

for LULCC are more fully considered (e.g. Foley *et al* 2011, Chabbi *et al* 2017). While reducing fossil fuel emissions of carbon dioxide must remain a priority for climate change policy (figure 5), policies addressing LULCC, especially tropical deforestation and other agricultural emissions, must be included in the agreements if we want to achieve low temperature targets, such as 2 °C warming such as pledged as part of the Paris agreements.

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